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13. ABSTRACT

The present report attempts to present a comprehensive review of achievements made under the support of a continuing series of related AFOSR Grants. The essence of all the work was to develop numerical simulations that capture the interactions among aerodynamics, rigid-body dynamics, structural dynamics, and control systems. All of these components of a flying airplane were viewed simply as elements of a single dynamic system. All the work led toward an end result in which a maneuvering aircraft could be simulated without resorting to wind-tunnel or flight tests. A major obstacle to this development is the fact that one must know the motion of the aircraft and its control-surface deflections in order to calculate the flowfield, and one must know the flowfield in order to calculate the aerodynamic forces and, from them, the motions. **One cannot determine the flowfield unless one knows the motion of the airplane and one cannot determine the motion unless one knows the flowfield. In this work the PIs have made significant advances in the development of the needed methodology.** By expanding the structural deflections in terms of the free-vibration modes, the principal investigators were able to covert the governing partial-differential equations of the structure into a system of ordinary-differential equations. The aerodynamic loads were obtained by refining and extending the vortex-lattice concept. However, it must be noted that both the aerodynamic model and the structural models used in the examples can be changed, by simply changing subroutines in the general code, without changing the general approach. Neither is essential nor even desirable for some other applications. An iterative scheme based on a predictor-corrector algorithm for systems of stiff ordinary differential equations was developed. A number of successes were achieved, which are described in the following text.

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FINAL REPORT OF GRANT NO. AFOSR 90-0032

AERODYNAMIC/DYNAMIC/CONTROL INTERACTION

by

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1. Abstract

The present report attempts to present a comprehensive review of achievements made under the support of a continuing series of related AFOSR Grants. The essence of all the work was to develop numerical simulations that capture the interactions among aerodynamics, rigid-body dynamics, structural dynamics, and control systems. All of these components of a flying airplane were viewed simply as elements of a single dynamic system. All the work led toward an end result in which a maneuvering aircraft could be simulated without resorting to wind-tunnel or flight tests. A major obstacle to this development is the fact that one must know the motion of the aircraft and its control-surface deflections in order to calculate the flowfield, and one must know the flowfield in order to calculate the aerodynamic forces and, from them, the motions. **One cannot determine the flowfield unless one knows the motion of the airplane and one cannot determine the motion unless one knows the flowfield. In this work the PIs have made significant advances in the development of the needed methodology.** By expanding the structural deflections in terms of the free-vibration modes, the principal investigators were able to covert the governing partial-differential equations of the structure into a system of ordinary-differential equations. The aerodynamic loads were obtained by refining and extending the vortex-lattice concept. However, it must be noted that both the aerodynamic model and the structural models used in the examples can be changed, by simply changing subroutines in the general code, without changing the general approach. Neither is essential nor even desirable for some other applications. An iterative scheme based on a predictor-corrector algorithm for systems of stiff ordinary differential equations was developed. A number of successes were achieved, which are described in the following text.

2. Background

The development of the background for the present effort began about 10 years ago with the development of an accurate numerical simulation of a subsonic wing-rock phenomenon for slender delta wings. The success of this effort was due to the innovation of treating the flowing air and the moving wing as elements of a single dynamic system. Subsequent to the successful completion of this task, an insightful analytical model of wing rock was developed. In the process of completing this task, the PIs uncovered serious flaws in another analytical model developed a little earlier under support from NASA and pointed out what corrective steps could be applied to the NASA model. The concept of treating the combined flowfield and vehicle as a single system was further extended to include elastic deformations of the lifting surfaces and interactions among aerodynamics, dynamics, and control systems.

The first example to be considered was the numerical simulation of flutter. The graduate student involved in the project was an employee of NASA. At the time, we were doing this work, we had several discussions with the people at NASA who subsequently developed similar simulations using other numerical models of the flowfield. For our work we received a Certificate of Recognition and a cash award from NASA. The next examples to be considered were the suppression of wingrock by means of trailing-edge flaperons, determination of trailing-edge flap-deflection history for optimal changes in pitch, and simulations of pitch control in unsteady ground effect.

2.1 Wingrock

2.1.1 Numerical simulations

Because wing rock is a subsonic phenomenon that occurs at high angles of attack in a vorticity-dominated flow and because experiments have shown that the phenomenon is independent of the Reynolds number, the principal investigators (PIs) elected to refine, extend, and then use a general unsteady vortex-lattice method to predict the aerodynamic loads. *The wakes are modelled as inviscid, rotational flowfields*. The basic requirements for any numerical model of an unsteady lifting flow are that the vorticity-shedding rate and the evolution of the nearfield wake be accurately predicted. To determine the rate at which vorticity is being shed into the stream, the PIs force the pressures on the upper and lower surfaces to be equal along the edges where the wakes adjoin the wings. To place a wake in its force-free position and thereby predict its evolution, the PIs convect the vorticity at the fluid-particle velocity. Such a model greatly reduces computing times and avoids the problem of grossly over-predicting the viscous dissipation of the vorticity. It is now clear that no dissipation, *i.e.*, an inviscid wake, is very close to reality at least for a dozen chord lengths or more downstream. The result was a very reliable, general vortex-lattice code.

Vortex-lattice codes, as well as other panel methods, have singularities along the edges of the elements. To remove this undesirable characteristic, the PIs developed a continuous-vorticity panel method. This approach, which is unique, directly provides, without any post-solution processing, a continuous, singularity-free velocity field on the surface of the vehicle. The details are given in the Ph.D. thesis of C. Mracek and Appendix A of this report.

The simulation of the PIs was the first successful numerical model of wing rock.*
Its success was a direct result of treating the flowing air and rocking wing as a single dynamic system. In some earlier work at WPAFB, a small-disturbance, transonic model was used to model the flowfield. This was the first time an integrated approach was used, and as far as the PIs know, theirs was the second.

The equations of motion governing the flowfield and the movement of the wing were solved simultaneously and interactively. This was a clear and sharp break with traditional approaches, which rely on wind-tunnel and/or flight-test data. In some cases, even static data are used. To treat the flowing air and wing as a single dynamic system, the PIs had to overcome a formidable

*Subsequent numerical models of the wing-rock phenomenon, those developed at NASA and those developed with support from NASA, use the so-called "modern methods" of simulating the flowfield. In this work, treating the wing and flowing air as a single dynamic system, a procedure introduced by the PIs, was also employed. However, the modern methods that were employed were restricted to supersonic Mach numbers and conical flowfields. It seems very unlikely that any aircraft will be flown at high angles of attack at supersonic Mach numbers, and the assumption of a conical flowfield is highly suspect.

obstacle: to calculate the aerodynamic loads on the vehicle, one must know its motion (in order to impose the boundary conditions on the flowfield); and to calculate the motion of the vehicle, one must know the aerodynamic loads. To break this apparent impasse, we developed an inherently nonlinear, iterative procedure based on a predictor-corrector algorithm. The approach is well-suited for systems of stiff, nonlinear equations and only requires the aerodynamic loads at integral time steps. The latter point is an important consideration for unsteady models of flowfields.

An interesting feature of the present approach is that the predicted aerodynamic loads depend on the present motion as well as the history of the motion. As the shed vorticity convects downstream, it forms the wake. There is a purely kinematical relationship, which is valid for viscous as well as inviscid flowfields, that provides the velocity field *induced* by the vorticity in the flowfield. *It is a kinematic truth that vorticity anywhere in a flowfield induces velocity everywhere.* The *induced* drag is a consequence of this fact. Thus, the wake can, and in the case of vorticity-dominated flows does, strongly influence the flowfield around, and hence the aerodynamic loads acting on, the vehicle. At any given instant, the vorticity in the wake was shed at various earlier times; hence, the wake "remembers" what happened earlier and serves as the "historian" of the flow. Because the position of the shed vorticity changes with time, its influence changes with time; thus, the motion and loads are not in phase. No other simulation developed so far has this capability. (The conical-flow assumption removes the possibility of capturing the upstream influence.)

The numerical simulation showed the surprising sensitivity of the wind-tunnel results to the damping in the bearing of the sting and the position of the axis of rotation. During the planning of the experiments both were thought to be of minor importance.

The numerical simulation also provided a "flow visualization" that revealed the physics of the phenomenon. The physical changes in the flowfield can readily be correlated with the corresponding changes in the restoring and damping components of the aerodynamic loads. The effect of an additional degree of freedom in pitch was also studied. The details are contained in the Ph.D. thesis of J. Elzebda and Appendix B of this report.

The numerical simulation provided both the motion and the aerodynamic loads. Therefore, it was possible to develop analytic expressions relating the loads to the displacement and velocity. These nonlinear expressions were substituted into the equations of motion and the resulting second-order, nonlinear differential equations were solved by perturbation methods. Such an analysis clearly reveals the way in which the various terms interact and influence the response.

2.1.2 Analytical models of wingrock

Using the results of the numerical study, the PIs developed an analytical model for the wing-rock phenomenon. They obtained an analytic expression for the aerodynamic moment as a function of the roll angle and its derivative. Their expression did not agree with the one proposed by Hsu and Lan. The PIs then showed that (1) their model predicted divergence (observed in the wind tunnel and predicted by the numerical simulation), but the model of Hsu and Lan did not, and (2) the results obtained from their model are slightly more accurate than those obtained from the model of Hsu and Lan. The PIs then explained how to modify the model by Hsu and Lan to make it more accurate and capable of predicting divergence. An interesting fact is that the analytical model of Hsu and Lan, though somewhat inferior, is considerably more difficult to analyze than the analytical model of the PIs. The details are given in Appendix C.

2.1.3 Simulated suppression by active control of trailing-edge flaperons

The PIs then moved into the next phase of the research by simulating the response of an unstable delta wing to motions of its flaperons. To the aerodynamic model of the delta wing, the PIs added trailing-edge flaperons*.

*Using the so-called modern methods to model the flow, others have attempted to simulate the control of supersonic wingrock. The suppression was effected by means of leading-edge flaps, instead of trailing-edge flaps. Because the modern methods are based on the

To the equations governing the motion of the delta wing and the flowing air, the PIs added a feedback control law to command the flaps and an equation describing the servo-mechanism that moves the flaps. Then the numerical algorithm was extended and all the equations were integrated numerically. The numerical simulation produced the motion of the wing, the unsteady flowfield, and the histories of the commands and the actual motions of the flaperons. It was shown that for a range of gains the oscillatory roll motion could be suppressed. More details can be found in Appendix D and the Ph.D. thesis of C. Mracek.

2.2 Unsteady Aerodynamic Interference

The most challenging situations to model are those in which one component of a configuration operates in or near the wake of another. The difficulty in simulating such situations is compounded when the flow is unsteady.

When one component of the configuration changes its effective angle of attack, the vorticity distribution on its surfaces simultaneously changes and so does the disturbance-velocity field induced by the surface vorticity. Consequently, the vorticity on the surfaces of all the other components in the vicinity simultaneously changes also. Virtually, all simulations of aerodynamic interference are capable of capturing this phenomenon. However, there is another aspect of unsteady interference that is far more difficult to simulate. The changing vorticity distributions on the surfaces of the configurations are accompanied by a change in the vorticity-shedding rates along the edges of the lifting surfaces that adjoin the wakes. These sudden and often substantial changes in the shed vorticity convect downstream; therefore, their influence on the distribution of vorticity over the surfaces of the configuration changes with time as a result of the changing relative position of the vorticity in the wake with respect to the components of the configuration. An event continues to influence the loads for some time after the event through the velocity

conical-flow assumption, they cannot be used to treat trailing-edge flaps; however, the approach described here can treat leading-edge as well as trailing-edge flaps.

induced by the vorticity shed as a result of the event and convecting downstream. Thus, any realistic model of an unsteady flow must accurately account for the history*.
Modelling this important aspect of an unsteady vorticity-dominated flow is rather difficult.

The general unsteady vortex-lattice method developed for a single wing models the wakes, accounting for the convecting vorticity. It was extended to account for multiple, closely coupled lifting surfaces. The method was used to simulate the flowfield for a configuration that resembles the X-29. More details are given in Appendix E.

Perhaps the most important and certainly the unavoidable interference occurs during take-off and landing, when the wings, tail and/or canard feel the presence of the ground. Capturing the influence of the ground on the wake is an important element of the model of the flowfield. The general unsteady vortex-lattice code was extended to simulate unsteady ground effects. More details are given Appendix F.

3. Numerical Simulations of Flutter, Gust Response, and the Suppression of Both

Before the collapse of the Soviet Union, there was a need for high-altitude, long-endurance (HALE) aircraft to be used to verify some of the provisions of the Strategic Arms Reduction Treaty (START). There is no longer a perceived need for HALE aircraft to verify some of the provisions of START but HALE aircraft are being developed to monitor the atmosphere. Boeing developed a HALE aircraft called the *Condor*. The very-high-aspect-ratio, very flexible wings of the *Condor* can experience wing-tip deflections as high as 25% of the span, as much as 10m in the case of the *Condor*.

*The conical-flow assumption, which is frequently employed in the so-called modern methods of modelling the flow, virtually eliminates the "history" of the motion from the model of the flowfield. There is no account of how vorticity released upstream affects conditions downstream as it convects.

Structural and aerodynamic models capable of accurately describing arbitrary large deflections and motions are essential for the numerical simulation of HALE aircraft in flight. The general unsteady vortex-lattice method developed by the PIs is not restricted by planform, camber, twist, angle of attack, or type of motion as long as the lines of separation are known and vortex-bursting does not occur near the lifting surfaces. Hence, it is very well suited for the simulation of HALE aircraft. It is interesting that the general vortex-lattice method has the capability of treating such a wide range of problems from low-aspect-ratio delta wings with significant leading-edge separation to very-high-aspect-ratio, very flexible wings experiencing large deformations in a rather large portion of their flight envelopes.

3.1 Flutter

The first example is the simulation of flutter of a high-aspect-ratio very flexible wing. The chain of events that transpire as the speed of the freestream increases at a given altitude is described next. At sufficiently low speed initial disturbances decay rather rapidly. The damping is entirely aerodynamic; we deliberately omitted structural damping to emphasize this point. Inviscid aerodynamic models do predict damping because they account for the transfer of energy from the structure to the stream. As the speed increases, the rate of decay decreases. Near the critical flutter speed the motion resulting from initial disturbances does not decay; instead, a limit cycle forms. As the speed increases, the amplitude of the limit cycle increases, and then at a critical speed, the motion begins to grow. Fast Fourier transforms reveal that the limit-cycle motion contains a single frequency.

The simulated behavior seems to mimic (at least qualitatively, perhaps quantitatively) the events observed in wind tunnels. The range of speeds in which limit cycles develop is small in the present example. When the approach was applied to the classic problem of a two-dimensional airfoil mounted on elastic supports (a problem discussed at length in the text by Y. C. Fung, the predicted behavior was similar. Unlike the models in wind-tunnel experiments and unlike the simulation, Fung's solution either decays or grows; there is no range in which limit cycles develop.

Details are in Appendix G.

The manuscript developed by the PIs is being submitted to the Journal of Aircraft.

3.2 Flutter Suppression

Also discussed in the manuscript of Appendix G is the use of a feedback-control/servo-mechanism system to drive the ailerons and suppress flutter and the response to gusts. The flowing air, wing, ailerons and entire active-control system for the flaps are treated as the elements of a single dynamic system. All the governing equations, including the control law that sends commands to the servo-mechanism driving the flap, are integrated simultaneously and interactively.

A very-high-aspect-ratio, very flexible wing, such as one might find on HALE aircraft, was also modelled. The wing was considered to be an inextensional beam, and nonlinear terms were retained in the equations of motion. In this case the elastic deformations of the wing were obtained simultaneously with the flow and aileron deflections. It was found in the simulation that flutter can readily be suppressed. This is true for linear as well as nonlinear models. More details are given in Appendix H and the M.S. thesis by J. A. Luton. The manuscript appearing in Appendix H has been accepted for the AIAA Journal.

3.3 Suppression of the Responses to Gusts and Random Disturbances in the Free Stream

In attempts to suppress the responses to gusts and/or random disturbances in the free stream, the PIs found that using trailing-edge flaps permitted either good control of torsional deflections or good control of flexural deflections, but not both simultaneously. Hence, they extended the aerodynamic model of the wing to include a leading-edge flap. Then controlling the leading-edge and trailing-edge flaps independently, they found that both torsional and flexural responses could be significantly reduced simultaneously.

A manuscript with J. A. Luton is currently being prepared for the AIAA Journal.

4. Other Developments Resulting from the AFOSR-Sponsored Research

The work done by the PIs in refining the unsteady aerodynamic model used in the simulations above has led to some interesting discoveries. It was shown by comparing computed results with observations made in a water tunnel that the formation of coherent vortical structures is almost completely an inviscid phenomenon. This work suggests that attempts to model such flowfields with the Navier-Stokes equations might be very difficult. Ironically, it appears that enough resolution must be achieved in order to accurately model (i.e., eliminate in this case) the viscous effects. For many such flowfields, perhaps a more efficient approach would be to begin with an inviscid model.

More details are provided in Appendix I. The manuscript found there will appear in the Journal of Fluid Mechanics.

Using the developments of the previous work, the PIs prepared and had accepted a "perspective" for the ASME Journal of Fluids Engineering. The manuscript is provided in Appendix J.

5. *Students Receiving Full or Partial Support*

The following students received full or partial support from the AFOSR Grants. The support took the form of stipends paid directly to them and/or money paid to the PIs to release them from other academic duties.

Masters Students

1. Dong, B. -N.: "Numerical Simulation of Two-Dimensional Lifting Flow," 1987.

2. Luton, A.: "Numerical Simulations of Subsonic Aeroelastic Behavior and Flutter Suppression by Active Control," 1991.

Doctoral Students

1. Elzebda, J.: "A Numerical Model of Unsteady Aerodynamic Interference," 1986.

2. Strganac, T. W.: "A Numerical Model of Unsteady, Subsonic Aeroelastic Behavior," 1987.

3. Mracek, C.: "Unsteady Potential-Flow Solution by Vortex Panels Coupled with Dynamics and Controls," 1988.

4. Nuhait, A.: "Numerical Simulation of Feedback Control for Lifting Surfaces in Steady and Unsteady Ground Effects," 1988.

5. Dong, B.: "Numerical Simulations of Wakes, Blade-Vortex Interaction, Flutter, and Flutter Suppression by Feedback Control," 1991.

6. Smith, M.: expected 1993.

7. Luton, A.: expected 1993.

6. Publications

The following articles were made possible by full or partial support from the AFOSR Grants.

Refereed Articles in Technical Journals and Proceedings for Which the Entire Manuscript is Reviewed

1. Konstadinopoulos, P., Mook, D. T., and Nayfeh, A. H., "Subsonic Wing Rock of Slender Delta Wings," J. Aircraft, Vol. 22, No. 3, 1985, pp. 223-228.

2. Kim, M. J. and Mook, D. T., "Application of Continuous Vorticity Panels to General Unsteady 2-D Lifting Flows," J. Aircraft, Vol. 23, No. 6, 1986, pp. 464-471.

3. Elzebda, J. M., Mook, D. T., and Nayfeh, A. H., "Influence of Pitching Motion on Subsonic Wing Rock of Slender Delta Wings," J. Aircraft, Vol. 26, No. 6, 1989, pp. 503-508.

4. Mook, D. T., Roy, S., Choksi G., and Dong, B., "On the Numerical Simulation of the Unsteady Wake Behind an Airfoil," J. Aircraft, Vol. 26, No. 6, 1989, pp. 509-514.

5. Elzebda, J. M., Nayfeh, A. H., and Mook, D. T., "Development of an Analytical Model of Wing Rock for Slender Delta Wings," J. Aircraft, Vol. 26, No. 8, 1989, pp. 737-743.

6. Nuhait, A. O. and D. T. Mook, "Numerical Simulation of Wings in Steady and Unsteady Ground Effects," J. Aircraft, Vol. 26, No. 12, 1989, pp. 1081-1089.

7. Nayfeh, A. H., Elzebda, J. M., and Mook, D. T., "Analytical Study of the Subsonic Wing-Rock Phenomenon for Slender Delta Wings," J. Aircraft, Vol. 26, No. 9, 1989, pp. 805-809.

8. ganac, T. W. and Mook, D. T., "A Numerical Model of Unsteady Subsonic Aeroelastic Behavior," AIAA J., Vol. 28, No. 5, 1990, pp. 903-909.

9. Mook, D. T. and Dong, B., "Application of Vortex Dynamics to Simulations of Two-Dimensional Wakes," Proceedings of the International Symposium on Nonsteady Fluid Dynamics, Toronto, Ontario, CANADA, FED-Vol. 92, June 4-7, 1990, pp. 435-448.

10. Mook, D. T. and Nayfeh, A. H., "Numerical Simulation of Dynamic/Aerodynamic Interactions," Comput. Sys. in Eng., Vol. 1, No. 2-4, 1990, pp. 461-482.

11. Mracek, C. P., Kim, M. J., and Mook, D. T., "Three-Dimensional Potential Flows by a Vorticity-Panel Method," Comput. & Fluids, in press.

12. Dong, B. and Mook, D. T., "On the Suppression of Flutter by Active Control," submitted for publication, J. Aircraft.

13. Luton, J. A. and Mook, D. T., "Numerical Simulations of Flutter and its Suppression by Active Control," accepted for publication, AIAA J.

14. Wilder, M. C., Mathioulakis, D. S., Poling, D. R., Dong, B., Mook, D. T., and Telionis, D. P., "On the Formation of Coherent Vortices," accepted for publication, J. Fluid Mech.

15. Mook, D. T. and Dong, B., "Numerical Simulations of Wakes and Blade-Vortex Interaction," accepted for publication, J. Fluids Eng.

16. Dong, B. and Mook, D. T., "On Numerical Simulations of Blade-Vortex Interaction," submitted for publication, AIAA J.

17. Luton, J. A. and Mook, D. T., "Suppression of Responses to Gusts and Random Disturbances by Active Control," to be submitted for publication, AIAA J.

Refereed Articles in Proceedings

1. Elzebda, J., Mook, D. T., and Nayfeh, A, H., "Steady and Unsteady Aerodynamic Interference in Closely Coupled Canard/Wing Configurations," Forum on Unsteady Flow Separation, The 1987 ASME Applied Mechanics, Bioengineering, and Fluid Engineering Conference, Cincinnati, OH, FED Vol. 52, June 14-18, 1987, pp. 37-44.

2. Mook, D. T. and Nayfeh, A. H., "Dynamic/Aerodynamic Interaction," Proceedings of the Workshop II on Unsteady Separated Flow, USAF Academy, Colorado Springs, CO, July 28-30, 1987.

AIAA, ASME, and SAE Conference Papers and Presentations

1. Konstadinopoulos, P., Mook, D. T., and Nayfeh, A. H., "Subsonic Wing Rock of Slender Delta Wings," AIAA Paper No. 85-0198, AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

2. Kim, M. J. and Mook, D. T., "Application of Continuous Vorticity Panels to General Unsteady 2-D Lifting Flows," AIAA 23rd Aerospace Sciences Meeting, Reno, NV, January 1985.

3. Mathiolakis, D., Telionis, D. P., Kim, M. J., and Mook, D. T., "An Investigation of Drifting Vortices," AIAA Paper No. 85-1621, AIAA Fluid and Plasma Dynamics, Cincinnati, OH, July 1985.

4. Elzebda, J., Mook, D. T., and Nayfeh, A. H., "Unsteady Aerodynamic Interference for Lifting Surfaces," AIAA Paper No. 85-1801-CP, AIAA Atmospheric Flight Mechanics Conference, Snowmass, CO, August 1985.

5. Mook, D. T. and Nayfeh, A. H. "Application of the Vortex-Lattice Method to High-Angle-of-Attack Aerodynamics," SAE Paper No. 851817, SAE Aerospace Technology Conference, San Diego, CA, October 1985.

6. Strganac, T. and Mook, D. T., "Application of the Unsteady Vortex-Lattice Method to the Nonlinear Two-Degree-of-Freedom Aeroelastic Equations,"

AIAA Paper No. 86-0867-CP, AIAA/ASME/ASCE/AHS 27th Structures, Structural Dynamics, and Materials Conference, San Antonio, TX, May 1986.

7. Mook, D. T., Roy, S., Choksi, G., and Alexander, D. M., "On the Numerical Simulation of the Unsteady Wake Behind an Airfoil," AIAA Paper No. 87-0190, AIAA 25th Aerospace Sciences Meeting, Reno, NV, January 1987.

8. Elzebda, J. M., Mook, D. T., and Nayfeh, A. H., "The Influence of an Additional Degree of Freedom on Subsonic Wing Rock of Slender Delta Wings," AIAA Paper No. 87-0496, AIAA 25th Aerospace Sciences Meeting, Reno, NV, January 1987.

9. Strganac, T. W. and Mook, D. T., "A New Method to Predict Unsteady Aeroelastic Behavior," AIAA Paper No. 87-0736-CP, AIAA/ASME/ASCE/AHS 28th Structures, Structural Dynamics and Materials Conference, Monterey, CA, April 1987.

10. Strganac, T. W., Mook, D. T., and Mitchum, Maria V., "The Numerical Simulation of Subsonic Flutter," AIAA Paper No. 87-1428, AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Honolulu, HI, June 1987.

11. Elzebda, J., Mook, D. T., and Nayfeh, A, H., "Steady and Unsteady Aerodynamic Interference in Closely Coupled Canard/Wing Configurations," Forum on Unsteady Flow Separation, ASME Fluid Engineering Spring Conference, Cincinnati, OH, June 1987.

12. Nuhait, A. O. and Mook, D. T., "Numerical Simulation of Wings in Steady and Unsteady Ground Effects," AIAA Paper No. 88-2546, in Collection of Technical Papers, pp. 246-257, AIAA Applied Aerodynamics Conference, Williamsburg, VA, June 1988.

13. Mracek, C. P. and Mook, D. T., "Numerical Simulation of Three-Dimensional Lifting Flows by a Vortex Panel Method," AIAA Paper No. 88-4335-CP,

AIAA Atmospheric Flight Mechanics Conference, Minneapolis, MN, August 1988.

14. Kim, M. J. and Mook, D. T., "Application of Continuous Vorticity Panels in Steady Three-Dimensional Lifting Flows with Partial Separation," AIAA Paper No. 89-0117, AIAA 27th Aerospace Sciences Meeting, Reno, NV, January 1989.

15. Mook, D. T. and Nuhait, A. O., "Simulation of the Interaction Between Aerodynamics and Vehicle Dynamics in General Unsteady Ground Effect," AIAA Paper No. 89-1498, AIAA Intersociety Advanced Marine Vehicles Conference, Washington, DC, June 1989.

16. Hytopoulos, E., Rodriguez, C., Schetz, J., and Mook, D., "Flow Over Inclined Finite Length and Width Flat Plates at Low and High Reynolds Numbers," AIAA Paper No. 90-1467, 1990, Seattle, WA, June 1990.

17. Mook, D. T. and Dong, B., "Application of Vortex Dynamics to Simulations of Two-Dimensional Wakes," invited paper, Joint ASME/CSME International Symposium on Nonsteady Fluid Dynamics, Toronto, CANADA, June 1990.

18. Mracek, C. T. and Mook, D. T., "Aerodynamic Potential Flow Panel Method Coupled with Dynamics and Controls," AIAA Paper No. 91-2846, AIAA Atmospheric Flight Mechanics Conference, New Orleans, LA, August 1991.

19. Mook, D. and Dong, B., "Flutter Suppression by Feedback Control," AIAA Paper No. 91-2847, AIAA Atmospheric Flight Mechanics Conference, New Orleans, LA, August 1991.

20. Luton, J. A. and Mook, D. T., "Numerical Simulations of Flutter and its Suppression by Active Control," AIAA Atmospheric Flight Mechanics, Hilton Head, SC, August 1992.

Other Talks, Lectures, Seminars, and Proceedings Publications

1. Mook, D. T., "Application of the Vortex-Lattice Method to Simulate Subsonic Aerodynamic Interference," Grumman Aerospace Corp., Bethpage, Long Island, NY, March 17, 1986.

2. Elzebda, J., Mook, D. T., and Nayfeh, A. H., "A Numerical Model of Unsteady Aerodynamic Interference," Tenth U.S. Congress of Applied Mechanics, Austin, TX, June 16-20, 1986.

3. Elzebda, J., Mook, D. T., and Nayfeh, A. H., "Numerical Simulation of Unsteady Aerodynamic Interference," 39th Annual Meeting of the Division of Fluid Mechanics, American Physical Society, Columbus, OH, November 23-25, 1986.

4. Elzebda, J., Mook, D. T., and Nayfeh, A. H., "Aerodynamic/Dynamic Interaction," 39th Annual Meeting of the Division of Fluid Mechanics, American Physical Society, Columbus, OH, November 23-25, 1986.

5. Mook, D. T., "Aerodynamic/Dynamic Interaction," invited seminar, Mechanical Engineering Department, Washington State University, Pullman, WA, December 1986.

6. Mook, D. T., "Aerodynamic/Dynamic Interaction," invited seminar, Aerospace Engineering Department, Ohio State University, Columbus, OH, January 21, 1987.

7. Mook, D. T. and Strganac, T. W., "Numerical Simulation of Subsonic Flutter," invited seminar, NASA Langley Research Center, Hampton, VA, June 23, 1987.

8. Mook, D. T. and Nayfeh, A. H., "Dynamic/Aerodynamic Interaction," invited presentation, AFOSR Workshop to Review Sponsored Research on Unsteady Separated Flows, Colorado Springs, CO, July 28-30, 1987.

9. Strganac, T. W. and Mook, D. T., "Nonlinear Dynamic/Aerodynamic Interaction with Applications to the Numerical Simulation of Flutter," Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Boca Raton, FL, November 18-20, 1987.

10. Mook, D T., "Transient Behavior of Lifting Surfaces in Ground Effect," invited seminar. CALSPAN Corporation, Buffalo, NY, March 18, 1988.

11. Mook, D. T., "Unsteady Aerodynamics," an invited series of three lectures. von Karman Institute, Brussels, BELGIUM, April 19-20, 1988.

12. Mook, D. T., "Aerodynamic/Dynamic/Control Interaction," seminar, Wright-Patterson Air Force Base, OH, September 1, 1988.

13. Nuhait, A. O. and Mook, D. T., "Simulation of the Interaction Between Aerodynamics and Vehicle Dynamics in General Unsteady Ground Effect," 1989 Intersociety Advanced Marine Vehicles Conference and Exhibit, Washington, DC, June 5-8, 1989.

14. Dong, B. and Mook, D. T., "Numerical Simulation of Wakes with Application to Blade-Vortex Interaction" invited paper, Third International Congress of Fluid Mechanics, Cairo, EGYPT, January 2-4, 1990.

15. Mook, D. T., "A New Method to Predict Unsteady Aeroelastic Behavior," NASA, Hampton, VA, February 26, 1990.

16. Dong, B. and Mook, D. T., "Numerical Simulation of Unsteady Aeroelastic Behavior," SECTAM XV 1990 Southeastern Conference on Theoretical and Applied Mechanics, Atlanta, GA, March 22-23, 1990.

17. Mook, D. T., "Numerical Simulations of Aeroelastic Behavior," Engineering Science and Mechanics Departmental Seminar, VPI&SU, Blacksburg, VA, September 21, 1990.

18. Mook, D. T., "Numerical Simulations of Aeroelastic Behavior," invited Midwestern Mechanics Seminar Series, University of Notre Dame, Notre Dame, IN, September 25, 1990.

19. Mook, D. T., "Numerical Simulations of Aeroelastic Behavior," invited Midwestern Mechanics Seminar Series, Illinois Institute of Technology, Chicago, IL, September 26, 1990.

20. Mook, D. T., "Numerical Simulations of Aeroelastic Behavior," invited Midwestern Mechanics Seminar Series, Purdue University, West Lafayette, IN, September 28, 1990.

21. Mook, D. T. and Nayfeh, A. H., "Numerical Simulations of Dynamic/Aerodynamic Interaction," Symposium on Computational Technology for Flight Vehicles, Washington, DC, November 5-7, 1990.

22. Dong, B. and Mook, D. T., "Numerical Simulation of Flutter Suppression by Feedback Control," Proceedings of the Second Pan American Congress of Applied Mechanics (PACAM), Valparaiso, CHILE, January 2-4, 1991.

23. Mook, D. T., "Numerical Simulation of Aerodynamic/Dynamic Interaction," invited Midwestern Mechanics Seminar Series, University of Minnesota, Minneapolis, MN, March 8, 1991.

24. Mook, D. T., "Numerical Simulation of Aerodynamic/Dynamic Interaction," invited seminar, Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, NY, March 15, 1991.

25. Mook, D. T. and Luton, J. A., "Aeroelastic Behavior of a Large Aspect Ratio Wing," Informal Fluid Mechanics Seminar, Department of Engineering Science and Mechanics, VPI&SU, Blacksburg, VA, March 27, 1991.

26. Dong, B. and Mook, D. T., "Numerical Simulation of Flutter Suppression by Feedback Control," Recent Advances in Active Control of Sound and Vibration, VPI&SU, Blacksburg, VA, April 15-17, 1991.

27. Mook, D. T. and Kim, M. H., "Transient Analysis of Propellers," SNAME Propeller/Shafting '91 Symposium, Virginia Beach, VA, September 17-18, 1991.

28. Luton, A. and Mook, D. T., *"On the Numerical Simulation of Unsteady* Aeroelastic Behavior," seminar, Wright Patterson Air Force Base, OH, September 30, 1991.

29. Elzebda, J. M., Mook, D. T., and Nayfeh, A. H., "Steady and Unsteady Aerodynamics of a Double Delta Wingship Design," Intersociety High Performance Marine Vehicle Conference and Exhibit, Arlington, VA, June 24-27, 1992.

30. Elzebda, J. M., Mook, D. T., and Nayfeh, A. H., "Numerical Simulation of Wingships," Intersociety High Performance Marine Vehicle Conference and Exhibit, Arlington, VA, June 24-27, 1992.

31. Luton, J. A. and Mook, D. T., "Suppression of Flutter by Feedback Control," Proceedings of the Third Pan American Congress of Applied Mechanics (PACAM), Sao Paulo, BRAZIL, January 4-8, 1993.

32. Mracek, C. P., Mook, D. T., and Nayfeh, A. H., "Numerical Simulations of the Interactions Among Aerodynamics, Dynamics, and Controls," Proceedings of the Third Pan American Congress of Applied Mechanics (PACAM), Sao Paulo, BRAZIL, January 4-8, 1993.

33. Mook, D. T., "On the Suppression of Flutter by Active Controls," seminar, Wright-Patterson Air Force Base, Dayton, OH, November 2, 1992.

34. Mook, D. T., "Wingships," The William Preston Society Annual Meeting, VPI&SU, Blacksburg, VA, November 13, 1992.